CONTRACT NAS 8-18037

ANALYTICAL STUDY OF NONMETALLIC PARTS FOR
LAUNCH VEHICLES AND SPACECRAFT STRUCTURES

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Prepared by

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Huntsville, Alabama

FOREWORD

This report presents work accomplished by The Boeing Company during the first quarter, July 1, to October 1, 1966, on "Analytical Study of Nonmetallic Parts for Launch Vehicles and Spacecraft Structures", NASA contract NAS 8-18037. The work is administered by the George C. Marshall Space Flight Center, P&VE Laboratory, Huntsville, Alabama. The NASA Technical Leader is Mr. Carl A. Loy.

Performance of this contract is under the direction of the Structural Development Unit, Spacecraft Mechanics and Materials Technology, Space Division, of The Boeing Company. Mr. C. F. Tiffany is Program Supervisor and Mr. D. H. Bartlett is Program Leader.

NOTE

Because this is a progress report, information contained herein is tentative and subject to changes, corrections, and modifications.

1.0 INTRODUCTION

The objective of this investigation is to determine the applicability of fiber reinforced plastics in spacecraft and launch vehicle structural components, with particular interest in the use of this type of structure to support cryogenic tanks. An additional objective is to compare the merit of these components with metallic parts of the same functional design. A survey of literature from past and current programs will be made to assemble information such as properties and methods of fabrication essential to the design phase. Parts will be designed utilizing the inherent advantages of reinforced plastic structure and comparisons made with designs of metallic parts. A quantity of parts will be fabricated and subjected to destruction tests intended to prove their suitability for the application selected.

2.0   SUMMARY OF WORK ACCOMPLISHED

The first month of contract effort was devoted to compiling Boeing and industry data on:

1. Physical and mechanical properties of glasses, resins, composites, and adhesives

2. Structural analysis techniques

3. Fabrication methods

4. Effects of space environments on stability and mechanical properties of composites and adhesive systems.

5. Applications of fiber reinforced structure related to the scope of interest of this program.

Upon completion of the survey certain materials were singled out for possible use in this program.   These are:

Roving or Yarn Reinforcements (unidirectional tapes)

  Scotchply XP-2340 Prepreg. (S-994 glass)

  Scotchply XP-2519 Prepreg. (S-994 glass)

  U. S. Polymeric E-787 Prepreg. (S-994 glass)

Glass Fabric Reinforcements

  181 cloth, S-994, glass fabric prepreg. (BMS 8-79)

    (Narmco 500, USP E777, 3M XD119, USP E787)

Wet Layup Resin Systems

  ERLA 2256/ZZLB 0820 (Epoxy)

  EPON 826/MNA (Epoxy)

  ERLA 0510/ZZL 0803 (Epoxy)

Adhesives

  Narmco 7343/7139 (polyurethane)

  Goodyear G-207 (polyester) possibly used as a primer for Narmco 7343.

  Phenolic-Polyamide liquid or tape with glass fabric carrier (BMS 8-30 or 5-17)

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Epoxy-Polyamide liquid (BMS 5-29)

Reinforcement

S-994 fiberglass yarn or fabric

Structural properties of composites to be used in design were taken from results of the Reference 1 contract. An example of room temperature properties is given in Table I.

The value marked with the asterisk has been arbitrarily reduced, based on Boeing data from similar composites. This appears reasonable since the compression and flexure values for the 1581 cloth in parallel and normal directions are nearly equal and in close agreement with Boeing data (Reference 2). The additional column entitled "edgewise shear" has been added from Reference 2. These values are used in design of the shear web of beams, rather than inter-laminar shear values.

Three general types of structural elements were selected for design. These are (1) pure tension members for cryogenic tank supports, (2) compression struts for cryogenic tank supports, and (3) beams for payload packages (noncryogenic). For the first item, member loads and lengths for design are taken from results of the Reference 3 contract. Two tension member end configurations are being considered in design. These are the laminated "foil" and "axe handle" concepts. Members of round and flat cross sections are being studied. The flat parts appear simplest to manufacture, however, the round parts should provide the least thermal interaction with multilayer insulation on cryogenic tanks. The lengths of interest for compression struts are in the range of 20 to 30 inches. Original estimates of ultimate loads for these members were 2500 to 5000 lbs; however, study has shown that fiberglass reinforced columns in these lengths only show weight savings over metallic materials when highly loaded, i.e., 12,000 pounds or more for a 20 inch member. The compression struts will be designed as tubular members with pinned ends.

LOWER TOLERANCE LIMITS AT 298°K

MATERIAL	SPECIMEN DIRECTION	TENSION, PSI	COMPRESSION, PSI	FLEXURE, PSI	INTERLAMINAR SHEAR, PSI	BEARING YIELD PSI	TENSILE MODULUS, PSI	EDGEWISE SHEAR, PSI
Unidirectional Filament Wound	Parallel	252,463	131,188	206,123	7,032	41,771	7,949,774	
Bidirectional Filament Wound	Parallel	137,965	87,445	165,523	4,482	33,606	5,008,400	
	45°	16,492	12,230	22,443	--	--	2,927,700	
	Normal	--	63,242	134,747	--	--	--	
1581 Cloth	Parallel	65,000*	58,225	99,278	6,455	31,810	3,062,848	11,000
	45°	14,196	26,782	35,836	--	--	1,552,381	27,000
	Normal	65,006	53,118	91,353	--	--	2,837,151	11,000
1543 Cloth	Parallel	160,773	83,240	126,491	7,228	34,186	5,042,851	
	45°	--	25,660	26,922	--	--	1,797,918	
	Normal	18,915	27,455	30,573	--	--	1,615,171	

TABLE I

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A preliminary analysis of beam construction has been completed. Beams with sandwich web, truss webs, and stiffened webs were considered to determine the least weight approach. No attempt was made to optimize the beam sections for each type of construction so the results should be treated as generalizations only. The results show that the sandwich web approach yields the most efficient design over the load range of interest. A computer optimization of this method of beam construction has been started. Various cross sections, spans and loading will be analyzed. A high strength aluminum beam will also be analyzed and comparisons made to show the range of spans and loading where fiberglass construction has a weight advantage.

3.0 ANALYTICAL APPROACH

Round Tubes in Compression (Reference 4)

The optimum design of tubular members in compression assumes the simultaneous failure in lateral buckling and local crushing.

The critical column buckling stress F_c is calculated from the Euler column formula by replacing the elastic modulus "E" with the tangent modulus "E_t" giving:

$$F_c = \frac{c\pi^2 E_t}{(L/\rho)^2} \tag{1}$$

multiplying both sides by a $F = P/A$ relationship, substituting tube geometrical properties, and the expression $L_e = L/\sqrt{c}$ results in the following equivalent equation:

$$F_c^2 = \frac{\pi E_t}{8} \times D/t \times P/L_e^2 \tag{2}$$

P/L_e^2 is called the structural index for a column, regardless of degree of end fixity, where L_e equals the effective column length.

The allowable local crushing stress of the tube should be determined by test. When test data is not available, the crushing stress is conservatively estimated by

$$f_c = \frac{2K\sqrt{E \times E_t}}{D/t} \qquad \text{where } K = .25 \tag{3}$$

By equating the crushing stress to the buckling stress an optimum value of D/t for the column is obtained:

$$D/t = \left[\frac{32K^2}{\pi} \times \frac{E}{P/L_e^2}\right]^{1/3} \tag{4}$$

It is interesting to note that the term E_t cancelled out, leaving only the elastic modulus, E, in the optimum relationship.

The maximum stress that can be developed in a tubular column may be found by substituting the value for optimum D/t from Equation (4) into Equations (2) or (3) giving:

$$f_c^3 = P/L_e^2 \times \frac{K\pi E^{\frac{1}{2}} E_t^{3/2}}{4}.$$

and rearranging terms

$$P/L_e^2 = \frac{4f_c^3}{K\pi E^{\frac{1}{2}} E_t^{3/2}} \qquad (5)$$

For a given material E_t is a known function of stress and Equation (5) may be plotted as a curve of stress versus P/L_e^2. To allow weight comparisons, the stress can be divided by material density and plots prepared as shown in Figure 1. It can be seen that the S-glass tube shows a significant weight advantage over high strength aluminum in the region of $P/L_e^2 > 30$.

Prior to the evaluation of S-glass for tubular columns the data from Reference 1 was reviewed. Page 34 shows typical load strain curves for bi-directional filament wound specimens in tension. Room temperature curves show there is little plasticity encountered before failure. It has been assumed that loading in compression would demonstrate similar stress strain relationships. Therefore, the calculations for S-glass in Figure 1 were performed assuming $E = E_t$ and the column curve would be as shown in Figure 2 below:
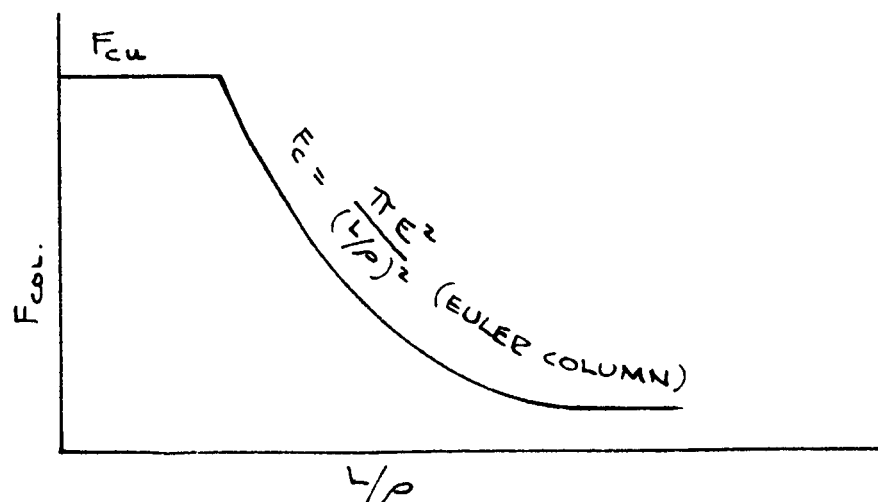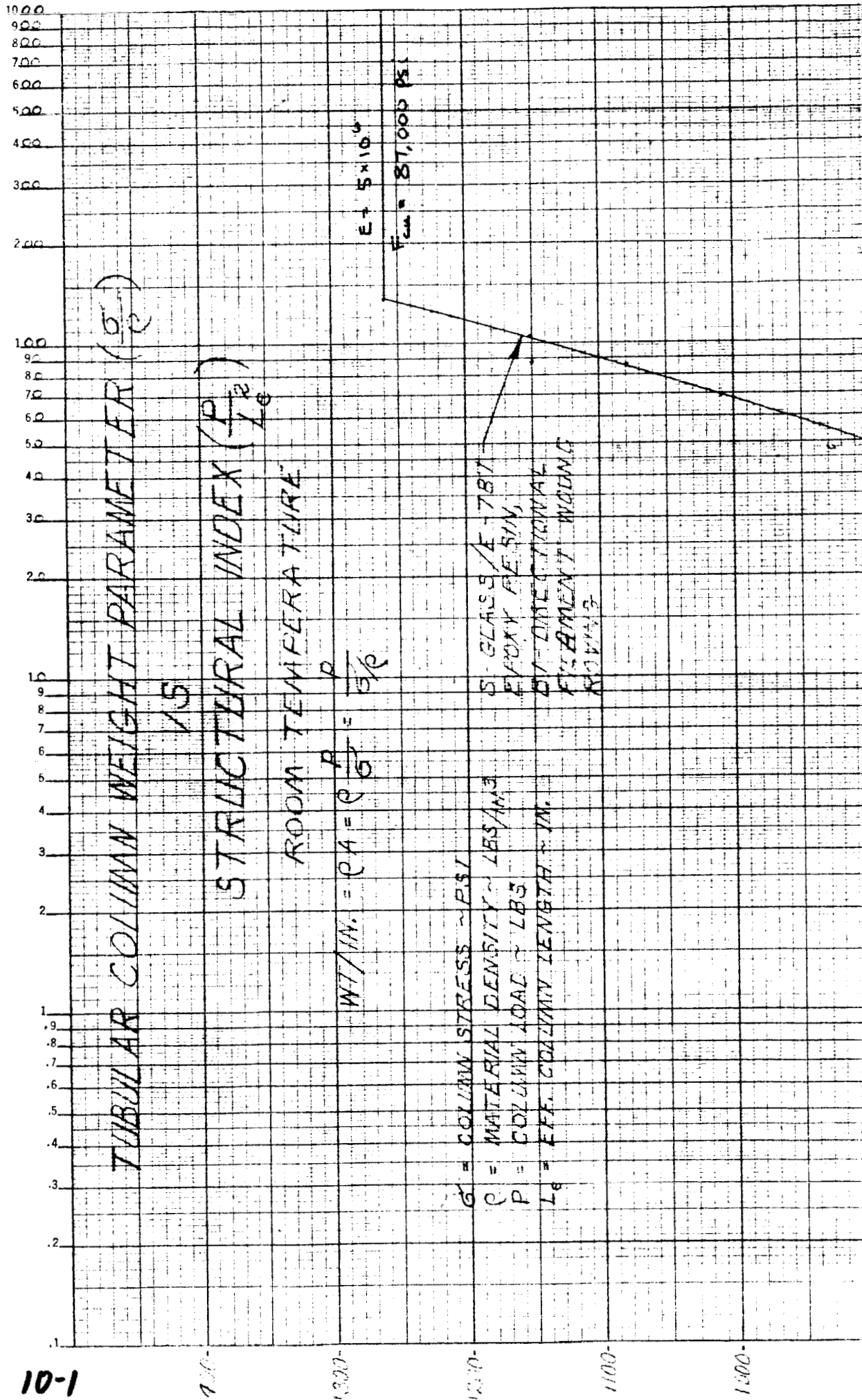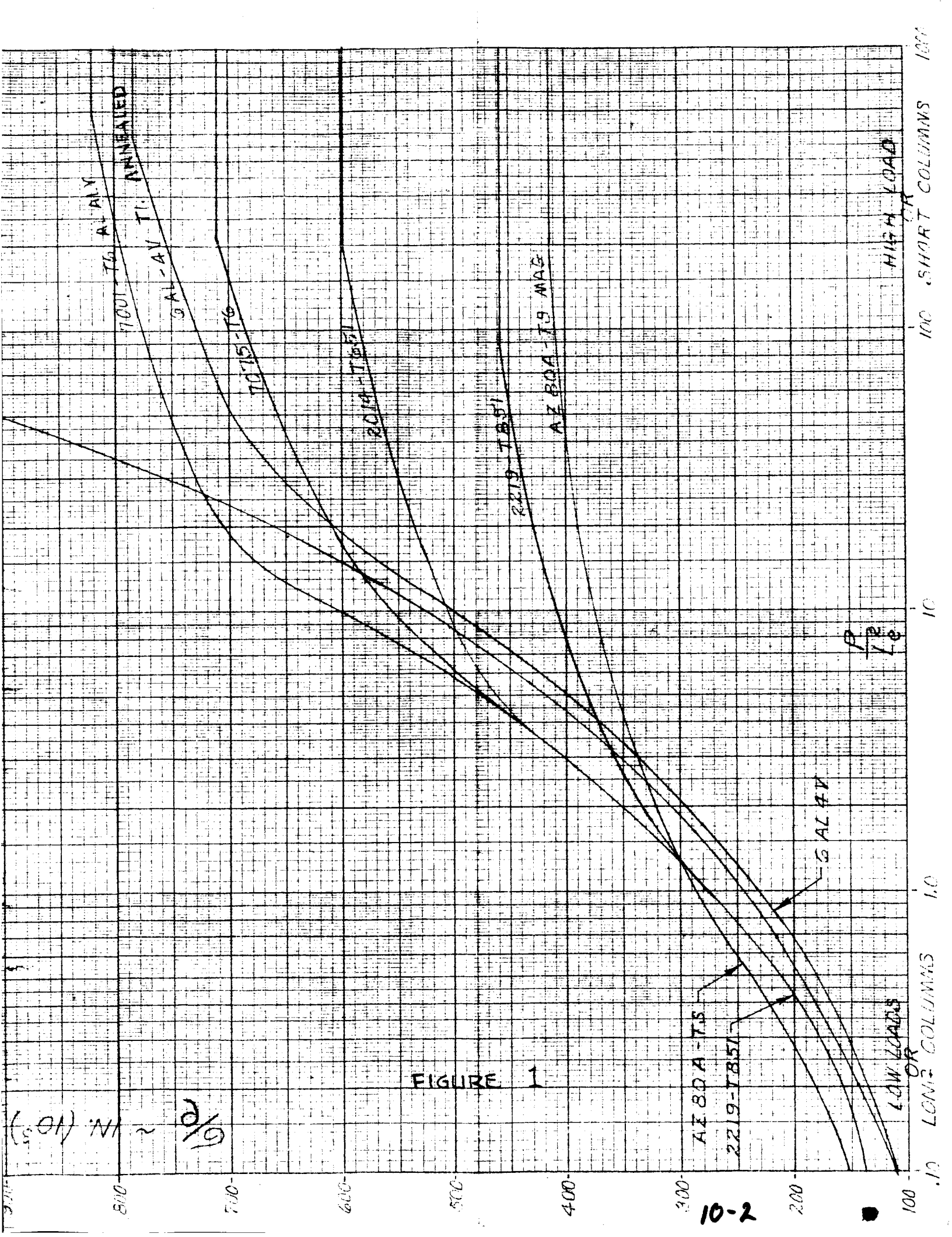

FIGURE 2

TUBULAR COLUMN WEIGHT PARAMETER ($\frac{\sigma}{\rho}$)

STRUCTURAL INDEX IS ($\frac{P}{L_e^2}$)

ROOM TEMPERATURE

$$\frac{W}{IN.} = \rho A = (\frac{\rho}{\sigma}) = \frac{P}{\sigma/\rho}$$

$E = 5 \times 10^6$

$F_{cu} = 87,000 \text{ psi}$

S-GLASS/E-787
EPOXY RESIN,
BI-DIRECTIONAL
FILAMENT WOUND
KIRKHILL

σ = COLUMN STRESS ~ PSI
ρ = MATERIAL DENSITY ~ LBS/IN³
P = COLUMN LOAD ~ LBS
L_e = EFF. COLUMN LENGTH ~ IN.

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FIGURE 1

The tube buckling test data from Reference 1 was analyzed to determine if the factor K = .25 is valid for use in the local tube crushing formula. The results of these tests and calculations are shown in the following table.

TYPE OF CONSTRUCTION	F_{cu} LBS/IN^2 STATIC (1)	E LBS/IN^2	F_{cu} LBS/IN^2 SHORT TUBE (2)	K (5)	F_{cu} LBS/IN^2 COLUMN (3)	F_{col} LBS/IN^2 CALCULATED (4)
S-Glass E-787 Resin BFW	87,445	5.008 x 10^6	65,300	.377	42,550	43,705
S-Glass E-787 Resin 181-Fabric	58,225	3.062 x 10^6	32,540	.307	25,260	26,759

(1) F_{cu} = Ult. Compression Stress - Lower tolerance limits at 298°K
   Ref. 1, Page 106 Parallel Direction

   E = Tension Young's Modulus - Parallel Direction

(2) Min. Test Values of Three Specimens, Reference 1, page 209.
   Tube Length = 1.5"   Inside Diameter = 1.395"
   Wall Thickness = .05"

(3) Min. Test Values of Three Specimens, Reference 1, page 210,
   Tube Length = 17", Pinned Ends, Inside Diameter = 1.331",
   Wall thickness = .05"

(4) Calculated $F_{col} = \pi^2 E/(L/\rho)^2$ Euler Column

(5) Assume $F_{crushing} = F_{cu \ short \ tube} = KE \ t/R \ (E_t = E)$

The calculations show that the value of K = .25 is conservative for S-glass tube crushing design. The last two items (F_{cu} and F_{col}) were included to show the correlation between calculated Euler column stresses and actual failure stresses from the tube tests.

It was shown from Reference 1 data that plasticity in tensile tests was insignificant, however, no compressive load strain data was found in the literature survey to verify the assumption for columns. It is apparent from Figure 1 that if this material does not show plasticity in compression, as the other materials do, a substantial ($\approx$ 35%) weight reduction over the other materials is possible in the region of $P/L_e^2 > 100$. This assumes that the Euler column formula is valid until ultimate compression is reached, as shown in Figure 2, provided the tube walls are thick enough to prevent local crippling. It is Boeing's opinion that compression struts in this region of P/L_e^2 should be fabricated and tested.

Since minimum heat leak is another item of interest, the thermal conductance of tubular columns for the full range of P/L_e^2 was calculated for all materials. The fiberglass reinforced plastic structure provided by far the lowest conductance of any of the materials listed.

Beams

The initial elastic buckling of flat plates in shear is given by

$$\gamma = \frac{\pi^2 K_s E}{12(1-\mu^2)} (t/b)^2 \tag{6}$$

where γ = shear stress

  K_s = plate buckling coefficient

  E = elastic modulus

  μ = Poisson's ratio

  b = short side of panel

  t = sheet thickness

To include nonelastic as well as elastic buckling, E can be replaced by $(E \times E_t)^{\frac{1}{2}}$ where E_t = tangent modulus of the material compression stress strain curve at a compression stress = $2 \times \gamma$ (maximum shear stress theory).

The average shear stress on the plate is:

$$\gamma = q/t \tag{7}$$

where q is the average shear flow applied to the plate.

Substituting Equation (7) into (6) and solving for q/b gives

$$q/b = \left[\frac{12\,(1-\mu^2)}{\pi^2}\right]^{\frac{1}{2}} \times \frac{\gamma^{3/2}}{K_s^{\frac{1}{2}}\,(E \times E_t)^{\frac{1}{4}}} \tag{8}$$

The term q/b is the loading index for flat plates in shear.

Values of q/b can be calculated for various materials and comparisons can be made by plotting versus γ/ρ (ρ = density). A high value of γ/ρ is desirable for low structure weight. Figure 3 shows γ/ρ versus q/b for some materials, including fiberglass cloth. It can be seen that the 181 S-glass cloth with E-787 resin does not appear as efficient as aluminum or magnesium for large panel sizes or for low load. However, for high loads or small panel sizes (i.e., honeycomb sandwich) the 181 S-glass cloth web can show some advantage. The curve for the fiberglass web was prepared using E as a constant and assuming isotropic properties. Reference 1 data shows some plasticity effects in tensile tests for cloth and it is logical to assume the same is true in shear. In practice then, this plasticity would cause some rounding off of the curves at high values of q/b, similar to the other materials. An examination of the curves of Figure 3 shows that significant weight savings are not possible with fiberglass cloth webs in pure shear applications.

Since a beam is primarily a combination of a shear web and column members for chords, some conclusions can be drawn from the study of these simpler members. It was shown in the foregoing analysis that fiberglass provided a slight weight advantage over 7075-T6 in the region of high q/b values, using a

FIGURE 3

PLATE WEIGHT PARAMETER vs.
LOADING INDEX $2\beta/b$
FOR FLAT PLATES IN SHEAR σ/ϕ

ROOM TEMPERATURE

6Al-4V [TI] 0
181 FABRIC

7075-T6

2024-T3 BARE

ALUMINUM (MAC)

$$\frac{\text{WEIGHT}}{\text{in}} = \sigma/\phi \cdot b \left[\frac{E_s \beta}{b} \right]^{1/2}$$

WEIGHT, σ/ϕ OF PANEL LENGTH

LOW LOADS OR
LARGE PANEL SIZES

HIGH LOADS OR
SMALL PANEL SIZES

ALUMINUM

MAGNESIUM

TITANIUM

FIBERGLASS

σ/ϕ

$2\beta/b \sim psi$

FIGURE 3

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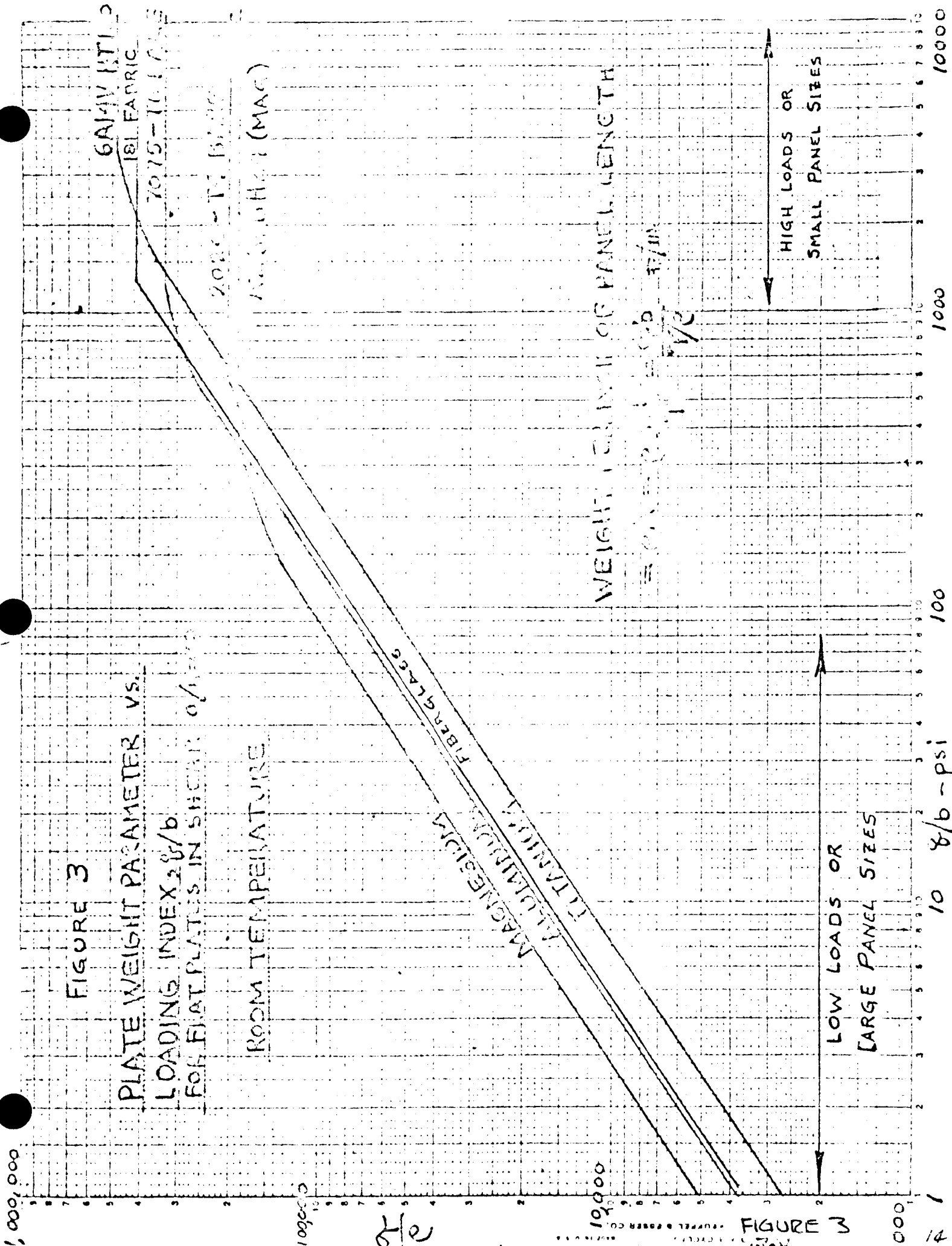
honeycomb web. From the column study it was shown that the fiberglass member
appeared to offer weight savings for the highly loaded or short columns.
It can therefore be concluded that a least weight fiberglass beam should be
constructed with honeycomb shear webs and chord members that are well stabilized
both laterally and vertically. This would tend to rule out truss type webs
where chord members are unsupported between truss members and intermediate
shear webs where chords may buckle inward.

To bear out these conclusions, a preliminary analysis of three types of "I"
beam construction was made. The types of construction were (1) sandwich web,
(2) stiffened web, and (3) truss web. Several designs for each type of
construction were considered and sketches of these are shown in Figures 4, 5,
6, and 7. Variables in the study were beam span, depth and loading. Figures 8
and 9 show the results of this study in terms of beam weight for two span
lengths and various methods of construction. The truss web concept selected
was the one described in Figure 6. All the concepts shown in Figure 5 were
rejected because analysis showed that with alternates 1 and 2, the truss
members were prohibitively heavy to prevent buckling and with alternate 3,
design and fabrication were complex. Both the intermediate shear and shear
resistant web concepts are as typified in Figure 7. The honeycomb web design
selected was alternate 2 in Figure 4. Alternate 1 was rejected because it
was difficult to load both unidirectional filament flanges due to low shear
modulus of the HRP core. Alternate 3 appears acceptable for higher loads,
however, for the load ranges considered only a small quantity of unidirectional
filaments were required which, if spread out in the form of a flange, would
incur instability problems.

From the curves of Figures 8 and 9, it can be seen that the honeycomb web
construction method yields the least weight for the longer spans considered
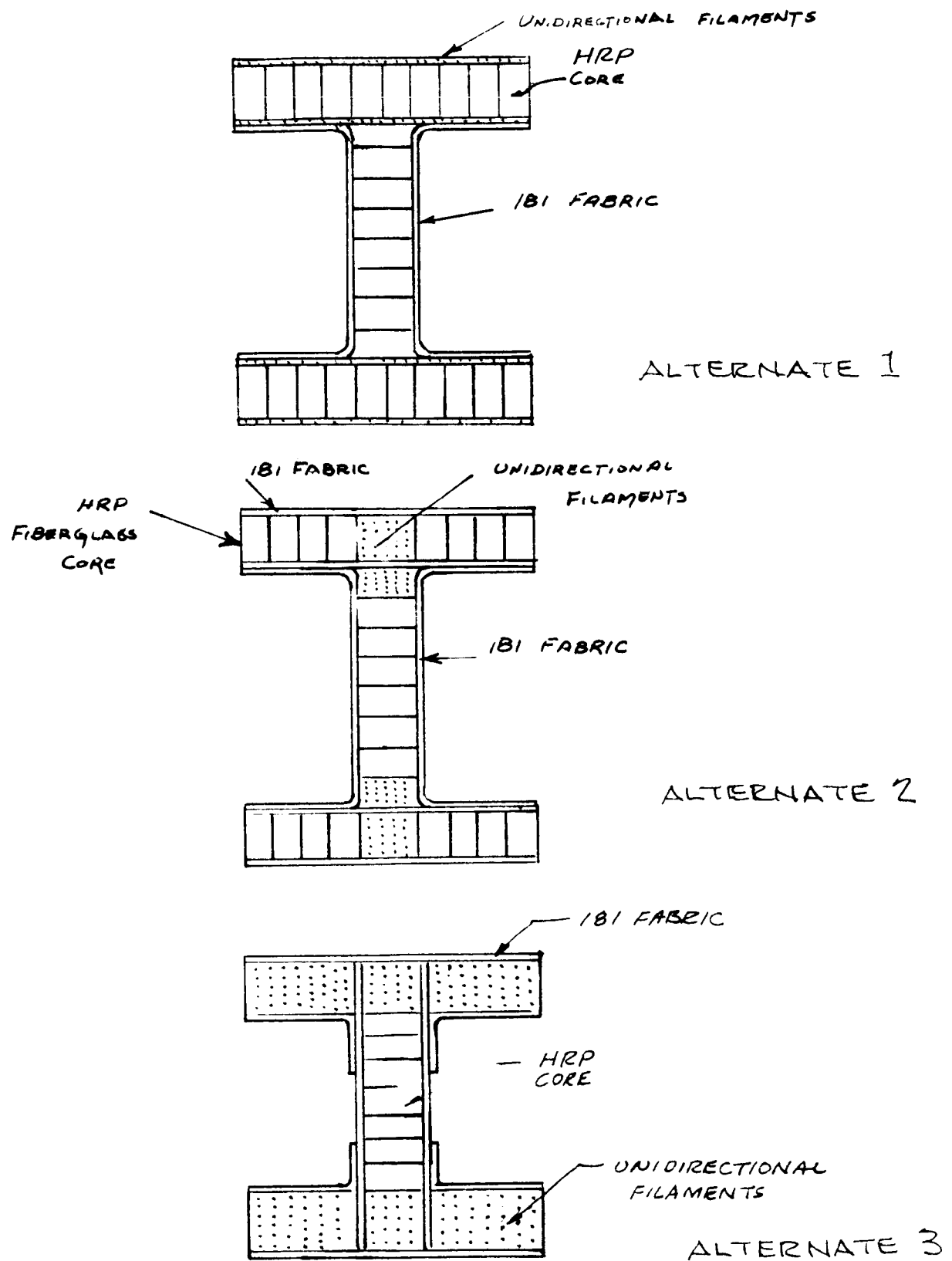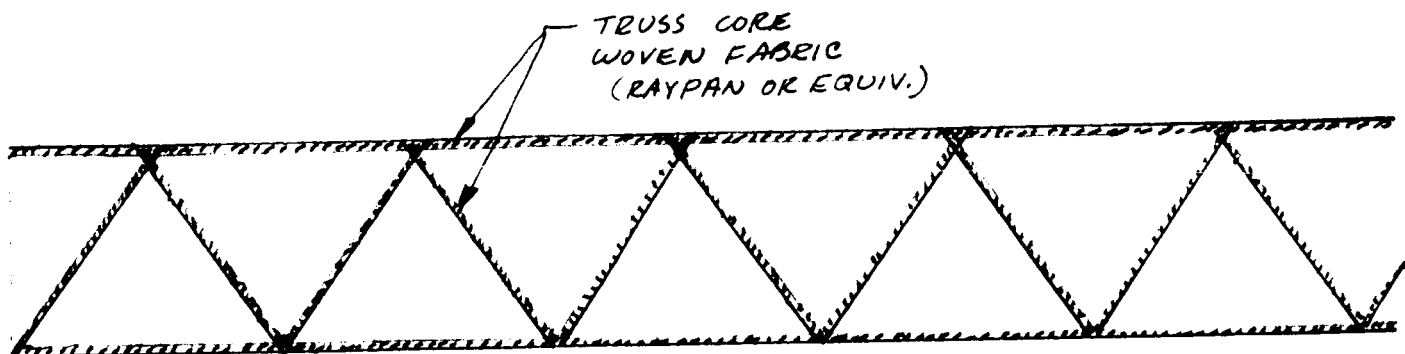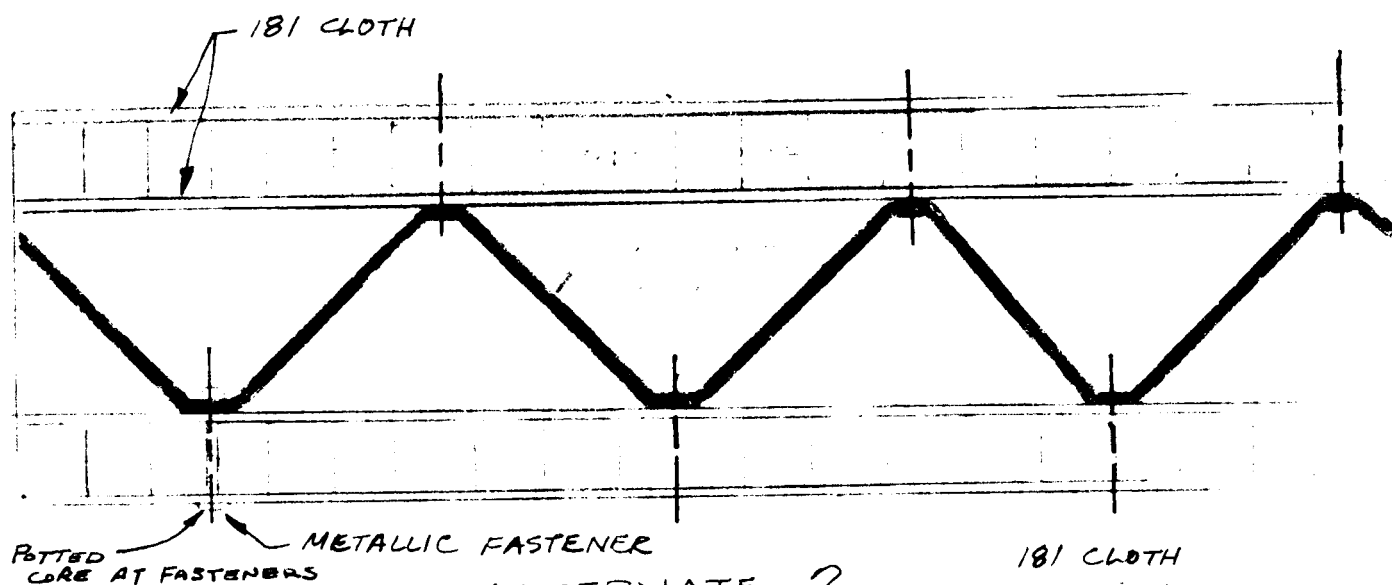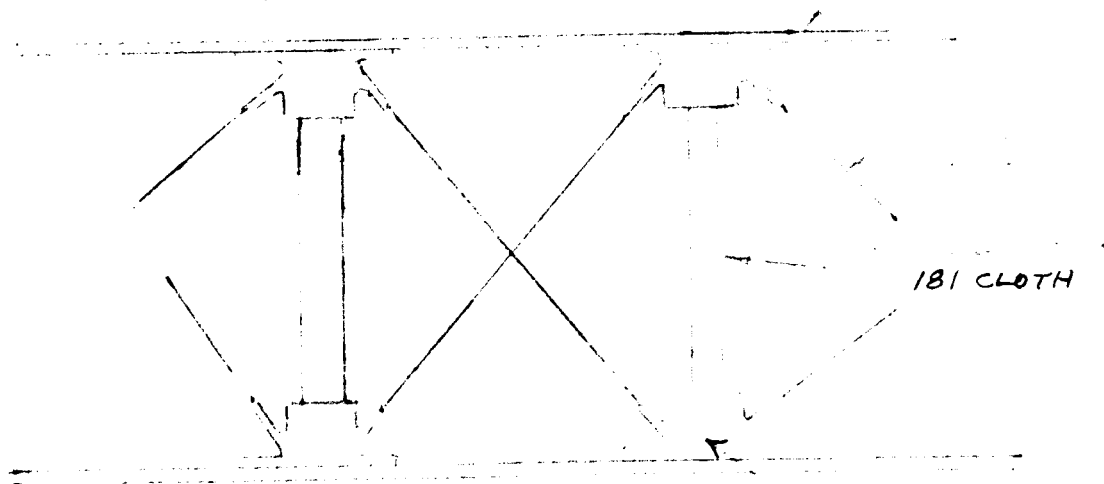and the shear resistant web for the shorter spans. For the shorter spans, the

UN.DIRECTIONAL FILAMENTS

HRP CORE

181 FABRIC

ALTERNATE 1

181 FABRIC

HRP FIBERGLASS CORE

UNIDIRECTIONAL FILAMENTS

181 FABRIC

ALTERNATE 2

181 FABRIC

HRP CORE

UNIDIRECTIONAL FILAMENTS

ALTERNATE 3

FIGURE 4   HONEYCOMB WEB DESIGNS

TRUSS CORE
WOVEN FABRIC
(RAYPAN OR EQUIV.)

ALTERNATE 1

181 CLOTH

POTTED
CORE AT FASTENERS   METALLIC FASTENER   181 CLOTH

ALTERNATE 2

181 CLOTH

ALTERNATE 3

FIGURE   5   TRUSS WEB DESIGNS

17

A

A

B

B

C

C

181 FABRIC

B-B

C-C

181
FABRIC

A-A

FIGURE 6 TRUSS WEB DESIGN

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HRP CORE

181 FABRIC
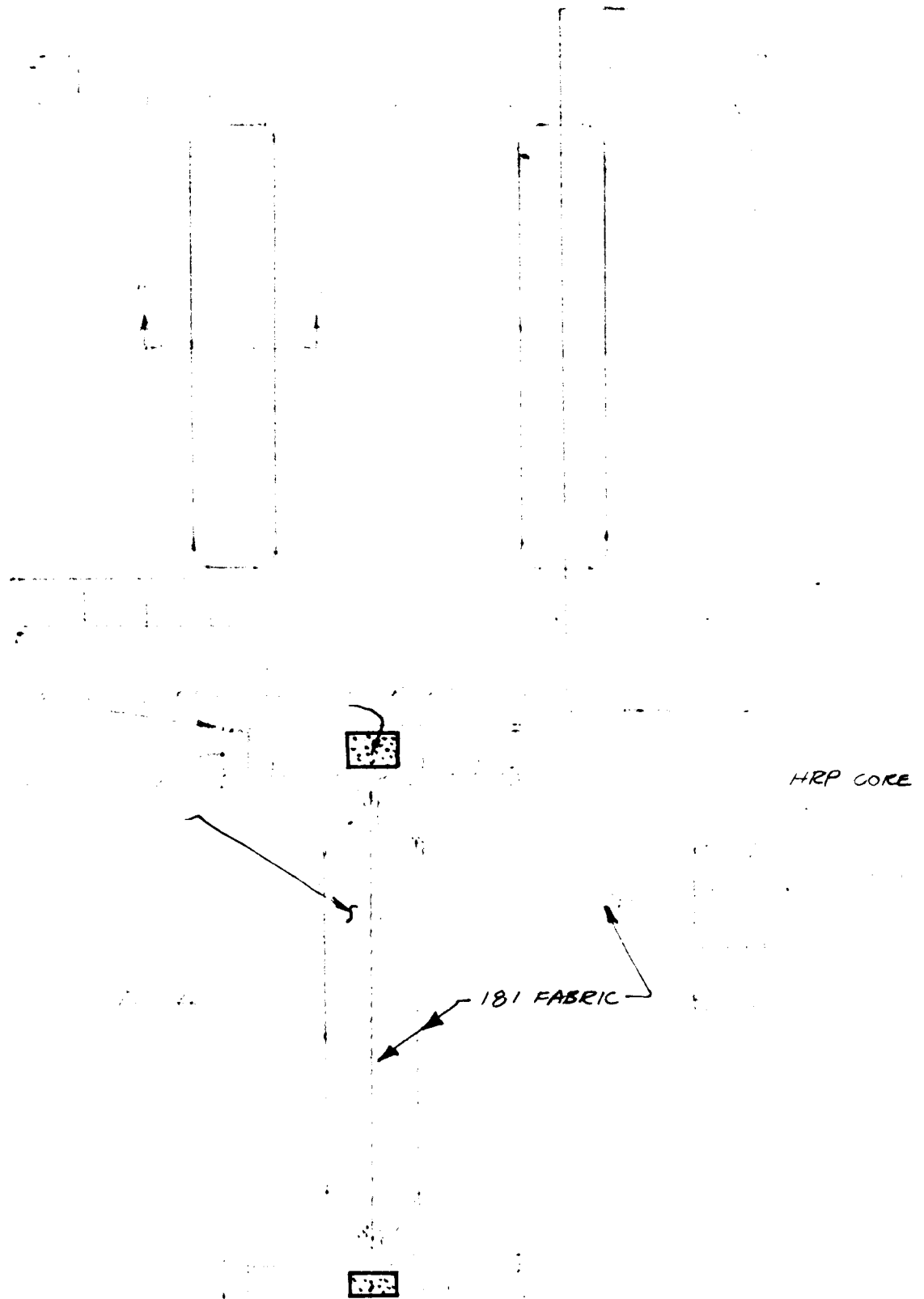
FIGURE 7 STIFFENED WEB DESIGN

WEIGHT OF BEAM ~ LBS/IN SPAN

P ~ LOAD ~ LBS

BEAM DEPTH = 3.0"

NOTE: BEAM DEPTH = 1.5" INVESTIGATED
AND FOUND TO BE LESS
EFFICIENT FOR ALL CASES

TRUSS WEB

INTERMEDIATE SHEAR WEB

HONEY...

SHEAR RESISTANT

2.1"

TYP.
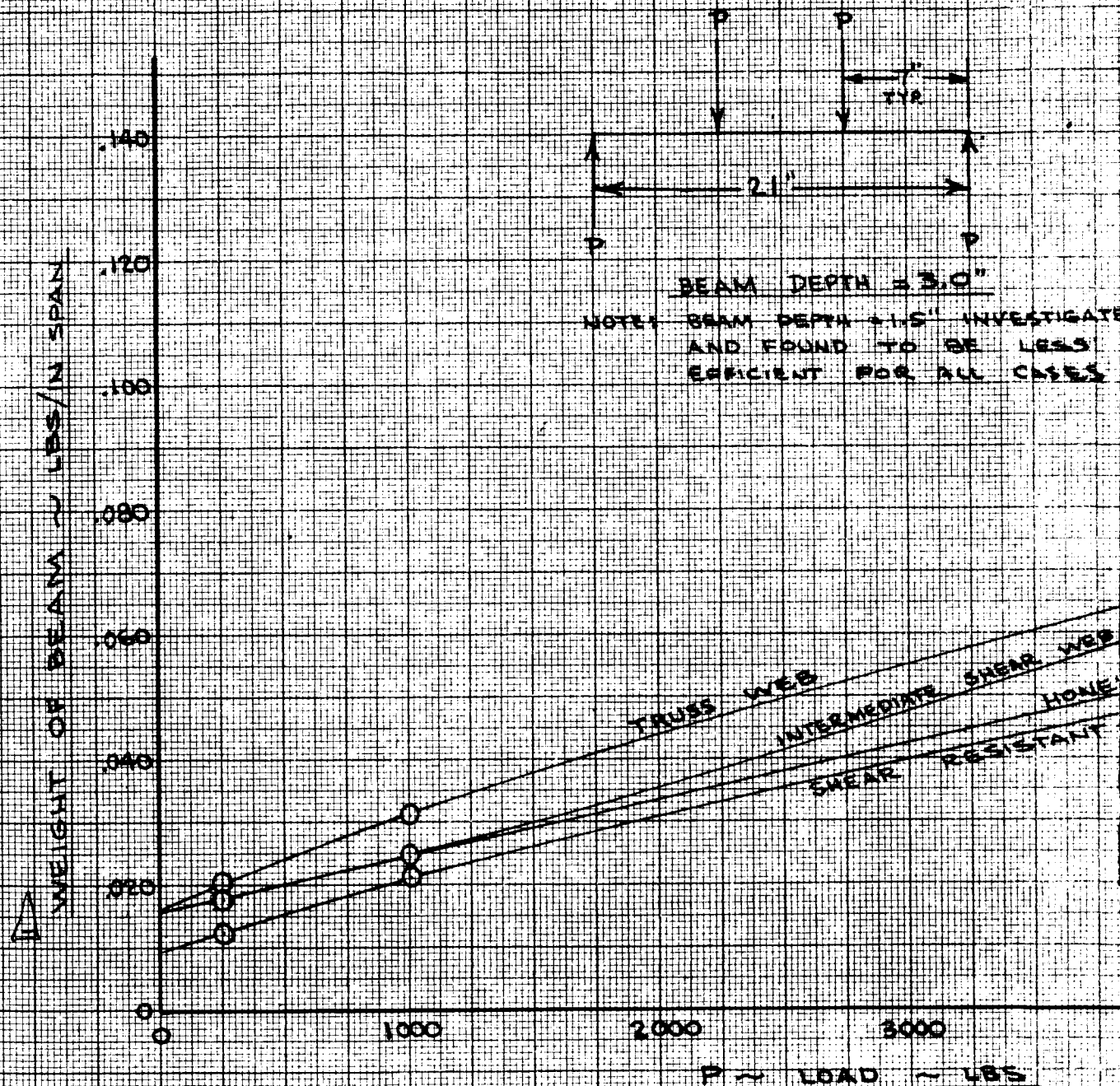
WEIGHT INCLUDES GLASS FABRIC,
UNIDIRECTIONAL FIBERS, HONEYCOMB CORE
HONEYCOMB BONDING MATERIAL, EDGE POTTING
COMPOUND ON OPEN HONEYCOMB EDGE, SHIMS AND
REINFORCEMENTS FOR TRUSS STRUT CONNECTIONS.
WEIGHT DOES NOT INCLUDE BEAM FITTINGS FOR
LOAD APPLICATION OR BEAM END SUPPORTS.

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BEAM — SIMPLY SUPPORTED — LATERAL RESTRAINT
PROVIDED AT ENDS AND AT LOAD POINTS.
SYMMETRICAL BEAM — CONSTANT SECTION
MATERIAL — S-GLASS / E-787 EPOXY RESIN
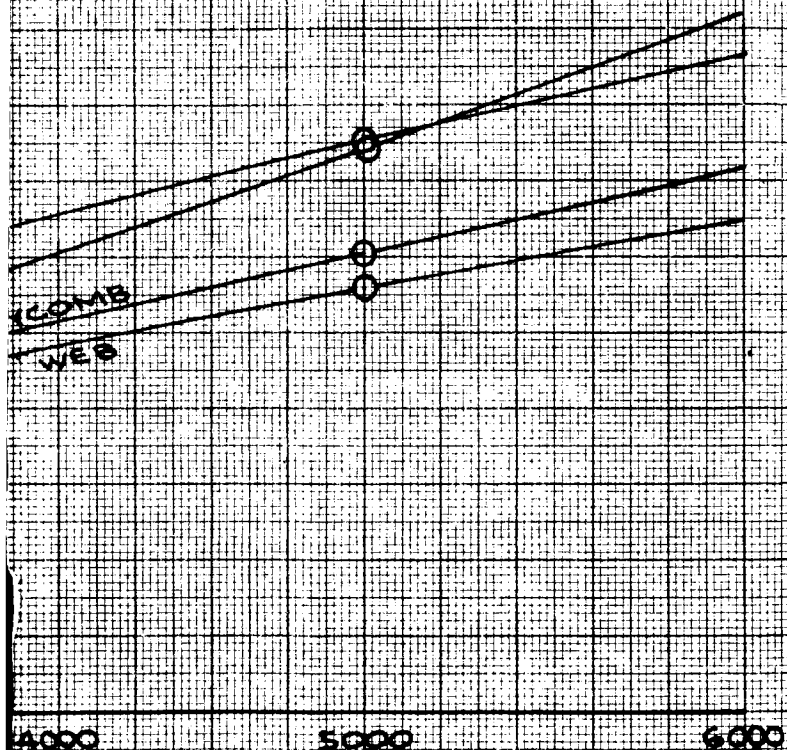181 CLOTH AND UNIDIRECTIONAL FILAMENT
HRP HEXCEL FIBERGLASS HONEYCOMB.

FIGURE 8

	INITIALS	DATE	REV BY INITIALS	DATE		TITLE		MODEL
CALC								
CHECK								
APPD								
APPD								

REV LTR

NOTE: BEAM DEPTH OF 4" & 8" INVESTIGATED
8" DEPTH WAS MORE EFFICIENT IN
FOR P = 250# FOR HONEYCOMB AND

WEIGHT OF BEAM ~ LBS/IN SPAN

P ~ LOAD ~ LBS

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BEAM – SIMPLY SUPPORTED – LATERAL RESTRAINT
PROVIDED AT ENDS AND AT LOAD POINTS.
SYMETRICAL BEAM – CONSTANT SECTION
MATERIAL – S-GLASS/E-787 EPOXY RESIN/ 181 CLOTH
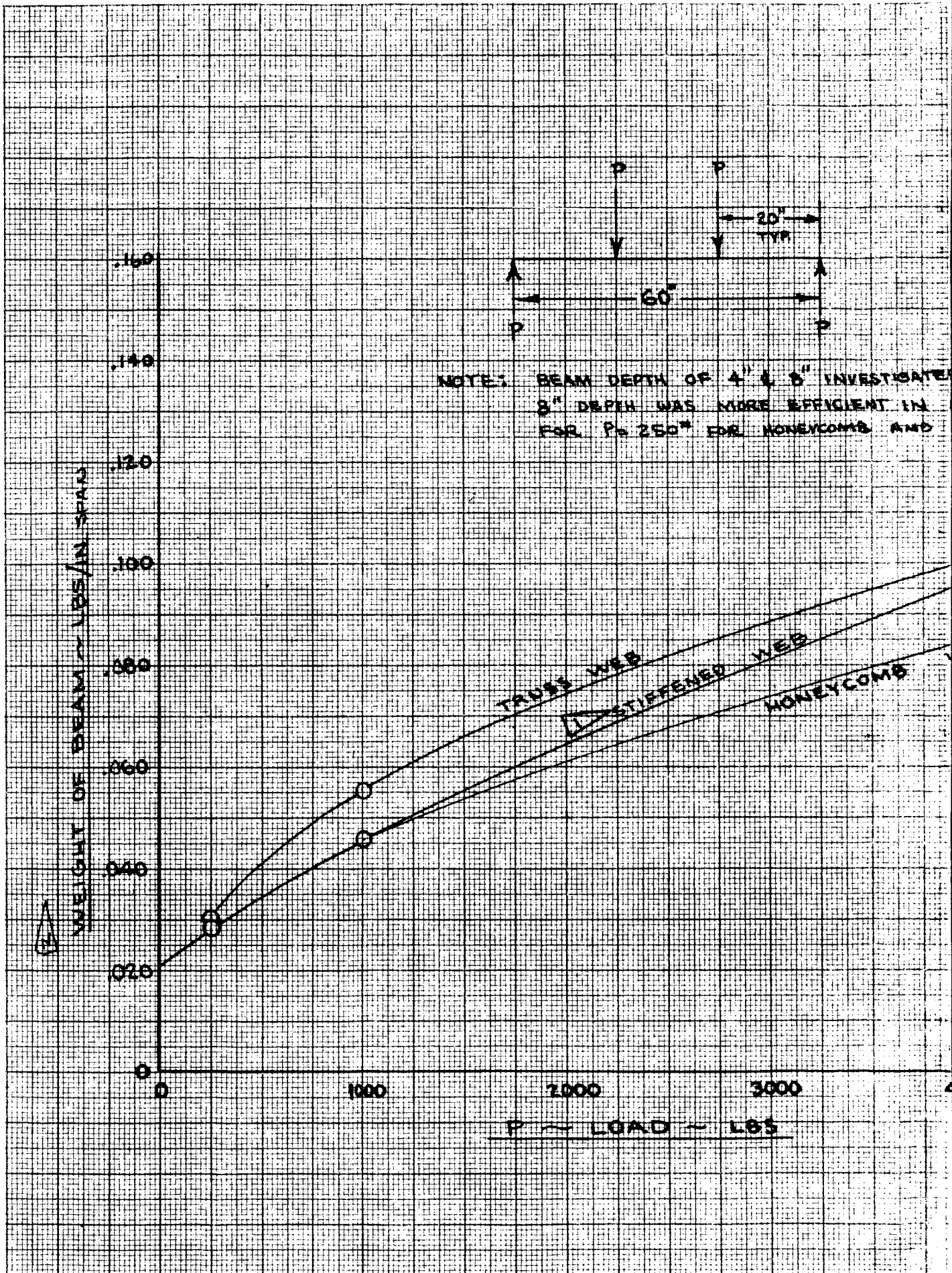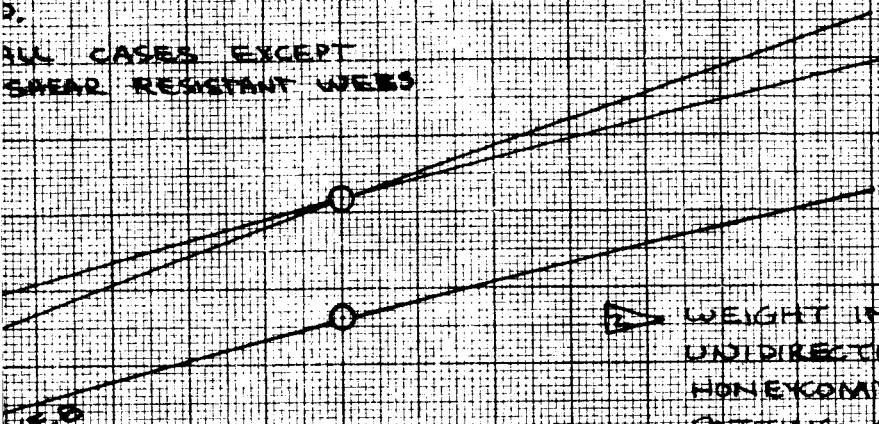AND UNIDIRECTIONAL FILAMENTS.
HRP HEXCEL FIBERGLASS HONEYCOMB

ALL CASES EXCEPT
SHEAR RESISTANT WEBS

WEB

WEIGHT INCLUDES GLASS FABRIC,
UNIDIRECTIONAL FIBERS, HONEYCOMB CORE,
HONEYCOMB BONDING MATERIAL, EDGE
POTTING COMPOUND ON OPEN HONEYCOMB
EDGE, SHIMS AND REINFORCEMENTS FOR
TRUSS STRUT CONNECTIONS - WEIGHT
DOES NOT INCLUDE BEAM FITTINGS
FOR LOAD APPLICATION OR BEAM
END SUPPORTS.

SHEAR RESISTANT OR
INTERMEDIATE SHEAR WEBS

FIGURE 9

5000   6000

	INITIALS	DATE	REV BY INITIALS	DATE		TITLE		MODEL
CALC								
CHECK								
APPD								
APPD								

REV LTR

BOEING | NO.
| SH

21-2

honeycomb web approach was only slightly heavier.

From this preliminary investigation it became apparent that the variation of weight with various methods of construction may not be great if each approach was optimized. For instance, for the 5000 lb load case and 60-inch span, the maximum beam weight was only 17% higher than the minimum.

The major problem in design was to prevent failure due to lateral buckling. Unidirectional fibers were used in the chords and these fibers have an $E = 7.95 \times 10^6$ which is lower than aluminum, yet their ultimate strength in compression is 150,000 psi (Reference 1). As a consequence, it is difficult to stabilize the chord members in compression while working at this high stress level. In the beam sizes investigated, only a very small cross section of unidirectional fibers were required, and for stability, it was necessary to add honeycomb flanges which in turn resulted in increased weight. It can be concluded that to show a substantial weight advantage over aluminum construction, beams of considerably greater load capacity (over 5000 lbs) where more uni-directional flange filaments are used, must be considered.

Box beams would provide good lateral stability but design loads should be even greater than for the "I" section for equivalent weight. This is due largely to the increased web area of a box beam necessitated by minimum gages and the construction features of a honeycomb web design. It is believed that certain features of "I" beams such as ease of attachment to flanges and simpler construction gives this approach an advantage over box designs.

It is planned to optimize the "I" section beam, with honeycomb web construction, for loads up to 20,000 lbs and spans to 60" through use of a computer program. The optimum S-glass beam will be compared to aluminum construction using the same design criteria and program. The beam geometry that is found to offer the most potential will then be used in fabrication and testing of a fiberglass part.

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